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Spatial diffusion of electric vehicles in the German metropolitan region of Stuttgart

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Abstract

At the moment, interest in electric vehicles (EVs) is increasing worldwide, mainly due to concerns about climate change and rising prices of fossil fuels. EVs still have some significant drawbacks compared to gasoline-powered cars. However, a small part of the population is expected to adopt this technology already within the next years, because higher purchase costs and lower driving range are of less concern to them. They are called the "Early Adopters" of EVs.

In this study we developed scenarios for the spatial diffusion of EVs up to 2020 in private households in the municipalities and urban districts of the metropolitan region of Stuttgart in Germany. First, hypotheses of Early Adopters of EVs were constructed based on social mobility profiles and the demands of car drivers. Secondly, the number of these potential adopters was calculated with statistical data for each municipality and urban district. In a third step, we developed a Bass diffusion model with System Dynamics to simulate the spatial diffusion of EVs

in the region of Stuttgart. The increase of EV-ownership in each Early Adopter-type in a single municipality depends on the chosen values of the parameters “Advertisement effectiveness”, “Contact Rate” and “Adoption Fraction” of the Bass model. Furthermore, neighbourhood effects were modeled such that the increase of EVs in one municipality also depends on the increase of EVs in the neighbouring municipalities.

In the baseline scenario, significant spatial differences in the diffusion of EVs up to 2020 become apparent: the highest number of EV-holders will be found in the urban areas of the region. There exist also differences in the number of EVs present at each Early Adopter-type: The “Urban trend-setter” is prevalent in the central districts of Stuttgart, while the “Multi-car family” is mostly located in the more rural municipalities of the region of Stuttgart. The “Dynamic senior citizen” is almost equally distributed in the urban and rural areas.

The results of the spatial distribution of potential adopters of EVs can be used for the automobile industry’s marketing campaigns as well as to identify the regional demand for EV charging infrastructure.

1. Introduction

Due to concerns about the scarcity of fossil fuels and the problems of climate change, there is an increasing interest in alternative drive technologies worldwide. In several countries there exist joint initiatives of the government, the automobile industry as well as of electric utilities to prepare the market for electric vehicles (EVs). Because of their limited range, EVs will be mainly used in urban areas for short distances. Thus, the development of a rollout plan for EV charging infrastructure will be one of the major challenges for urban planners in the next years. To decide on the right locations for EV charging stations it is, however, imortant to know, where users of EVs live and what their mobility profiles are. The objective of this study is therefore, to investigate in a case study of the German region of Stuttgart, how EVs might diffuse in the coming years and whether there are spatial differences in diffusion.

In the “Nationaler Entwicklungsplan Elektromobilität” (national plan to develop electromobility) the German government expresses the target of having 1 Mio EVs driving on German roads up to 2020 (Bundesregierung 2009). Main drivers for innovations in electromobility are the German regulations on restrictions on CO_2-emissions of new cars, the creation of low emission zones in cities as well as the rising oil prices. With the economic stimulus package the German government spends 500 Mio. € for the promotion of electromobility in Germany. The money is used for research and development in battery technology as well as for testing different concepts of electromobility in eight selected model regions in Germany, with the region of Stuttgart being one of them (BMBVS 2009).

Due to their limited range and high purchase costs EVs are not attractive to the majority of car drivers today. The question is: Who will be the Early Adopters of EVs? Some studies on the diffusion of EVs exist already, though without investigating spatial differences in the diffusion of EVs (Becker, Sidhu et al. 2009; Feller and Stephan 2009; Nemry and Brons 2010). The objective of our study is to examine the spatial diffusion of EVs in the German region of Stuttgart and to build scenarios on the distribution of EVs on municipality and urban district level for the year 2020. The analysis will only focus on privately owned EVs that depend on recharging, thus excluding hybrid EVs (HEVs) and plug-in EVs (PHEVs).

In the following section we will shortly describe the theory of diffusion of innovation and the state of the art of studies on the diffusion of EVs (section 2 and 3). Based on studies on attributes of persons who have already adopted or are willing to adopt an EV, and on social mobility profiles, we will build hypothesis on Early Adopters of EVs (section 4). In section 5 we will describe the model of the diffusion of EVs and finally build scenarios for the year 2020 (section 6).

2. The theory of the diffusion of innovations

Diffusion of innovations in time and space has been widely investigated in geographical studies (Gould 1975; Allaway, Berkowitz et al. 2003; Madlener and Schmid 2008). Until now EVs represent an innovation in the automotive sector which is only used by a very small number of car drivers, and it is unclear whether or when the technology will enter the mass market (KBA 2010). The theory of the “Diffusion of innovations” by Rogers (1962) can help, however, to get some insights of the future market development of this innovative technology.

2.1 The process of diffusion and attributes of innovations

According to Rogers (2003) diffusion is “the process in which an innovation is communicated through certain channels over time among the members of a social system” (Rogers 2003, p.5).

Thus, communication is essential for the diffusion of an innovation. The adoption of an innovation is, however, an action that is taken by each person individually.
The diffusion process starts with an innovation-decision, where the individual seeks for information to reduce uncertainty about the advantages and disadvantages of an innovation. In this process mass media help to create knowledge about an innovation. To form and change attitudes towards a new idea, however, interpersonal communication is vital, since most of the individuals evaluate an innovation on the experience of persons in their social network who have already adopted the innovation. Depending on the degree of innovativeness, Rogers defines five adopter types. The earlier an individual adopts the new idea, the higher is his degree of innovativeness. The time-sequence is as follows: 1. Innovators, 2. Early adopters, 3. Early majority, 4. Late majority, and 5. Laggards. According to Rogers, innovators are usually better educated, have a higher social status, are more exposed to mass media and interpersonal communication and are more cosmopolitan than the other adopter types. The diffusion process starts with a small number of innovators, followed by a rising number of adopters until the market is saturated. In this process the rate of adoption is the relative speed with which an innovation is adopted and the cumulative number of adoptions over time usually forms an S-shaped curve (Rogers 2003).
People owning an EV nowadays can be classified as innovators. They are willing to take a risk and are interested in the new technology. The next generation of adopters will base their decision to buy an EV not only on the studied technical (dis)advantages of the vehicle but on the experience of near peers who already use EVs: The final decision for or against an EV depends on whether friends or neighbours that drive an EV are convinced of the technology.

Rogers (2003) distinguishes among five attributes of innovations which will be discussed here with reference to EVs.

- The **relative advantage** of an innovation describes the degree to which this innovation is better than the product or idea it substitutes. The relative advantage is mostly measured in costs, but may also be a sign of higher status or prestige. Due to high battery costs and relatively low oil prices, EVs cannot compete with the conventional cars yet. Further disadvantages are the limited range and long charging times. On the other hand convenient recharging at home and the comfort of silent and low-emission driving represent some important advantages. Emotional aspects of personal image and status can also be an important benefit. Owners of EVs can distinguish themselves as being environment-friendly and future-oriented.

- **Compatibility** of an innovation is the degree to which the new technology confirms the existing values and satisfies the personal needs. Concerning the driving functionalities of EVs they can be compared to conventional cars. Usage patterns only have to be adapted to the limited range and long recharging times.
- Low **complexity** of an innovation is an important advantage, because the technology can be understood and used by a greater part of the population. In general, driving of EVs is similar to cars with combustion engine, but with no need to change gears. The main difference is that refuelling habits have to be changed to plugging the EV to the electric grid.
- The **triability** of an innovation is crucial for the diffusion of a technology, since one often only becomes aware of the advantages and disadvantages of a new product by testing it. The introduction of EVs in the concept of car-sharing allows potential adopters to get familiar with the new technology and to overcome prejudices.
- The **observability** describes the degree to which the innovation is visible to others. The greater the number of EVs already circulating on the streets, the simpler it is to convince potential adopters to also buy an EV.

2.2 Spatial diffusion of innovations

The first advances in the research on the spatial aspects of diffusion were made by Hägerstrand in "Innovation Diffusion as a Spatial Process" (1953, 1967). He focused on the demand side of innovation diffusion and studied the adoption behaviour of individuals and the process of communication of information about the innovation. He states that diffusion occurs in a spatial context and affects the flow of information. Therefore remoteness and lower hierarchical order within a spatial system causes smaller volumes of information flow and increased time to adoption of the innovation (Hägerstrand 1973).

Due to the rise of information and communication technologies such as the internet, information is, of course, less space-dependent than in former times. To be convinced of a new technology, however, the innovation must fulfil the above stated attributes. Thus, the more EVs exist on the streets, the easier it is to be assured that the technology works well. If there are EVs in one's own neighbourhood, one might even test the car and discuss with the neighbours about its advantages and disadvantages.

A major shift in the research on diffusion of innovations was made by Brown (1981) who stresses that the focus on the demand side cannot sufficiently explain the differences in innovation diffusion and adoption. In the "market and infrastructure perspective" he explores the role of diffusion agencies and their strategies to induce adoption among the population in their service areas (Brown 1981, p.50). In the current state, the electromobility in Germany is largely pushed from the supply side. It is the joint initiatives of automobile industry, electricity suppliers and the local authorities that promote the EVs in selected urban areas ("Modellregionen") (BMBVS 2009).

3. Diffusion of EVs in selected countries

Several times in the past, EVs competed with gasoline cars, but today the technology is not present in the mass market (Cowan and Hultén 1996; Fréry 2000). Due to the scarcity of fossil fuels and the increasing sensitivity to climate change, several governments worldwide set up new favourable conditions that may lead to further market penetration of EVs. The German government, for example, spent 500 Mio € to promote electromobility. The objective is to have 1 Mio EVs by 2020 circulating on German roads (Bundesregierung 2009). Latest technological progress in battery and automotive research as well as rising oil prices could promote the development of the EV market.

In this section, studies on the diffusion of EVs worldwide and explicitly for the German market are shown followed by a summary on the opportunities and barriers for the diffusion of EVs.

3.1 State of the art: studies on the diffusion of EVs

The majority of studies dealing with the diffusion of clean-fuel vehicles are from the United States, especially California. EVs are usually studied as only one alternative of vehicles with clean drive technologies, compared to Hybrid Electric Vehicles (HEV) or Plug-in Hybrid Electric Vehicles (PHEV). To estimate the future market development of the technologies and to analyse the barriers for diffusion, household surveys and expert interviews were conducted

(Brownstone, Bunch et al. 1994; Leiby and Rubin 2003). Most studies use, however, a modeling approach to find out the influential factors for diffusion and to build scenarios of market penetration of EVs (Cao 2004; Becker, Sidhu et al. 2009; Sullivan, Salmeen et al. 2009). In these studies the Bass-Diffusion Model was applied, which is also widely used in marketing research (Bass 1969; Meade and Islam 2006). The results of the number of predicted EV/PHEV/HEV differ, however, substantially, depending on the assumptions of the models. A meta-study on the existing market forecast of EV and PHEV shows the great variety of results for the years from 2020 to 2050 (Hacker, Harthan et al. 2009): In the pessimistic scenario, there is no market penetration before 2015 (25% in 2050), whereas in the optimistic scenario the share of new car sales could already reach 20% in 2020 (80% in 2050).

Feller et al. (2009) and Justen (2009) analyse the EV diffusion in the German market. Both studies predict a market penetration of EVs of 2-3% in 2020 and of 16-18% in 2030 (Feller and Stephan 2009; Justen, Schmid et al. 2009). The share of sales is, of course, higher (7% in 2020, 45% in 2030 according to Feller et al. 2009). Both studies are based on the assumption of battery technology improvements and Justen also assumes rising oil prices.

The studies mentioned give quantitative forecast of EV development for Germany as a whole. Though the modeling results of Feller et al. depict regional differences in the distribution of EVs, they do not describe the diffusion of EVs in the single regions in detail. The aim of our study is therefore to concentrate on one region and to depict the spatial differences in the future diffusion of EVs on municipality-level.

3.2 Opportunities and barriers for the diffusion of EVs

The studies on future market penetration of EVs are based on technological and political assumptions and show which parameters influence the diffusion of EVs. Hence, major opportunities and barriers for the diffusion of EVs can be inferred.

The principal disadvantage of EVs is the low energy capacity of the lithium-ion battery of about 120-160 Wh/kg (Sauer 2010). The range of a EV with a usual battery capacity of 16.5 kWh is limited to approximately 100 km, depending on vehicle size and driving circumstances (slope, use of air condition, heating, light) (Priemer 2010). Another obstacle is high battery costs of around 1000 €/kWh (Hacker, Harthan et al. 2009). Thus, the future of electromobility will highly depend on the development of battery technology (Feller and Stephan 2009; Justen, Schmid et al. 2009; Nemry and Brons 2010).

A major influence on the market gain of EV is seen in rising oil prices. Assuming constant electricity prices, EV can compete with conventional cars on substantially lower driving costs (Cao 2004; Becker, Sidhu et al. 2009; Haas and Kloess 2009; Justen, Schmid et al. 2009). For the take-off of EV diffusion the availability of public charging infrastructure will be crucial (Feller and Stephan 2009; Justen, Schmid et al. 2009; Nemry and Brons 2010). Car drivers will only get convinced of electric drive technologies with limited range if they can be sure to find a recharging point when needed. Without communication about the new technology, EVs will not be diffused to large parts of the population. The studies showed that awareness and knowledge of the EV technology is important to raise a critical mass of adopters (Cao 2004; Feller and Stephan 2009).

Some diffusion models demonstrated that favourable political conditions can be drivers for EV diffusion. Thus, diffusion of EVs can be triggered by purchase incentives or vehicle tax exemptions (Leiby and Rubin 2003; Haas and Kloess 2009; Sullivan, Salmeen et al. 2009). Increasing concerns on energy security could lead to a further promotion of electromobility to reduce dependency on oil imports.

Furthermore, EVs are often part of the discussion on CO_2- free mobility, if the electricity is generated by renewable energies. The rising awareness of the population on climate change, could lead to more environmental friendly ways of mobility and to a shift to electric drive systems. The use of EVs can also reduce local emissions of air pollutants and noise in the cities.

If technical problems are solved, EVs can be used as a means of energy storage in times of high energy production. Although overall energy consumption of EVs is relatively low, EVs – charged at low electricity tariffs at night – could shave peak loads by feeding the surplus energy into the grid ("vehicle-to-grid") (Kempton, Tomic et al. 2001).

Finally, it can be stated that electromobility will gain rising importance, if advancements in battery technology are achieved. The speed and rate of adoption of EVs in Germany will, however, also be influenced by political conditions, EV costs, energy price developments, the availability of charging infrastructure, the awareness of consumers and their motivation to invest in environmental friendly vehicles. To develop scenarios about the future spatial diffusion of

EVs in Germany, attributes of Early Adopters of EVs and their spatial distribution must be known.

4. Adoption of EVs – the individual purchase decision

Since EVs are still in an early stage of development, they do not yet satisfy the needs of the majority of car drivers. Thus, the question is: Which part of the population is today and in the upcoming years interested in the use of EVs? Who are the Early Adopters of EVs?
In the following section, studies that analysed the attributes of potential Early Adopters of EVs are discussed. Furthermore, the mobility behaviour of different social groups is shown since it can also indicate high or low probability of future EV use.

4.1 Attributes of potential Early Adopters of EVs

According to Rogers (2003) (section 2), the diffusion process starts with people that are interested in new technologies and that have enough money to afford technological innovations. It is also assumed that electromobility will be triggered by car drivers who buy an EV for environmental reasons and who are willing to adapt their driving behaviour to the restrictions of the current EV technology. A US study, conducted in the city of New York, shows that Early Adopters of EVs did not base their purchase decision on the density of charging infrastructure or local tax incentives. The use of EVs is rather seen as a possibility of an environmentally friendly lifestyle, for which they are willing to change their driving and parking behaviour (New York City 2010).
Slater (2009) describes the results of a survey of households that already drive an EV and those who have demonstrated significant interest in purchasing an EV in the UK. He finds out that Early Adopters place higher value on green motoring and are less sensitive to higher capital costs. EVs are mainly purchased by multi-car households with higher average income, education and the availability of off-street parking (Slater, Dolman et al. 2009). A study conducted by the Shell company shows similar results: Early Adopters are mainly high-income households with higher education level who mainly live in cities and demonstrate interest in new technologies (Lane and Potter 2007).

The planning of charging infrastructure of the city of London also includes the location of "hot spots" of Early Adopters. They assume that Early Adopters of EVs have the same attributes as persons already using an HEV or EV today. Thus, hot spots of Early Adopters of EVs will be found, where there is a high number of households with off-street residential parking, that own more than one car and that commute over distances between 10 to 50 miles return (Mayor of London 2009).

Arnold et al. (2010) state that EVs will be part of new mobility concepts. Mobility surveys of young people in cities show that the number of private car ownership decreased over time and that the young generation rather chooses the most cost efficient and the most flexible means of transport. Therefore, private ownership of EVs in cities is not as important as the integration of EVs in car-sharing. Thus, users would not have to rely on private parking spaces and recharging facilities to charge "their" EVs (Arnold, Kuhnert et al. 2010).

4.2 Social mobility profiles and their influence on electromobility

Different social groups show substantial differences in their mobility behaviour. A study from the German institute of economic research (2004) shows, that the choice of vehicle type as well as the average distance travelled per day, are related with the variables income, age and sex. Thus, the analysis of the mobility profiles allows identifying which social group has a high potential to use EVs in the future (Vollmer, Kunert et al. 2004).

The higher the income, the more important the private car is as the main means of transport. The number of private cars owned rises with income: 67% of all households with a monthly net income of 3.600 € hold two or more cars (Vollmer, Kunert et al. 2004). This underlines the findings on attributes of Early Adopters from the previous section: households with higher income own more cars and thus could replace one car by an EV.

Income and the daily average kilometres travelled are also correlated. The mobility of households usually increases with the net income. Males earning 500 € monthly or less travel 24 km daily, whereas males in the highest income class (3600 € monthly) travel on average 58 km per day (Vollmer, Kunert et al. 2004). This could have a negative impact on electromobility, because the social group that could afford an EV has higher mobility standards which could in turn conflict with the limited range of EVs.

Mobility behaviour also differs between men and women, since women travel on average fewer kilometres daily. In the highest income class, women only travel 38 km, compared to 58 km of men. This is probably due to women being more often responsible for household chores such as buying groceries or bringing kids to the kindergarden or school (Stete and Klinkhart 1997). Thus, women would be one target group for EVs, since for them the limited range of EVs is of less concern.

Main differences in mobility patterns can be found among different age classes. People between 20 and 55 years old, show the highest distances travelled per day. From 55 years on, the daily distance travelled decreases rapidly with age. Senior citizens could therefore be one of the future EV-users. Furthermore, statistics show that from 2002 to 2008 the number of driving licences of people older than 65 years increased. The number of elder people driving a car for daily use also rose in the same time. In contrast, the young generation from 18 to 24 years old, prefers to use public transport, while the use of private cars decreased in the last years (INFAS and e.v. 2009; Arnold, Kuhnert et al. 2010).

4.3 Hypothesis on Early Adopters of EVs

Based on the theory of diffusion of innovations of Rogers (2003), and on the above described attributes of Early Adopters and social mobility profiles, hypotheses on three types of Early Adopters of EVs were constructed (Figure 1). These Early Adopter types will then be used for modelling the diffusion of EVs in the region of Stuttgart (section 5).

1. **The urban trend-setter**

   The urban trend-setter describes young persons between 18 and 35 years old, living in single or couple households with a relatively high education level and income.

   We assume that the young, well educated generation has a greater interest in new technologies than the average and is flexible enough to adapt to the new attributes of EVs. High income allows for purchasing an EV which is more expensive than a conventional car. The urban trend-setter does not have own children yet and thus, has enough money to spend on an EV.

2. The multi-car family

This Early Adopter-type describes families, owning at least two cars and that have a high average income, high education level and live in detached or semi-detached houses.

We assume that the first car is used for regular commuting to work, while the second car is only used for occasional travels, like for shopping or for picking up the children from school. Thus, the second car could be replaced by an EV. As described in section 4.1 people with higher income and education level are more likely to invest in EVs, because the interest in new technologies is higher and they are less sensitive to higher capital costs of EVs. Since they live in (semi-) detached houses they have an own garage or the possibility of off-street parking, where the EV can be recharged.

3. The dynamic senior citizen

The third group of Early Adopters are people between 60 and 75 years old, living in couple in detached or semi-detached houses, owning high capital.

The demographic development shows that the number of elder people will increase in the coming years and that this group still remains mobile. At the same time, the daily distance travelled by this age class is significantly lower than that of younger people, thus coinciding with the limited range of EVs. After their childen have left the house they often remain living in their (semi-) detached house, having an own garage and the possibility of recharging at home.

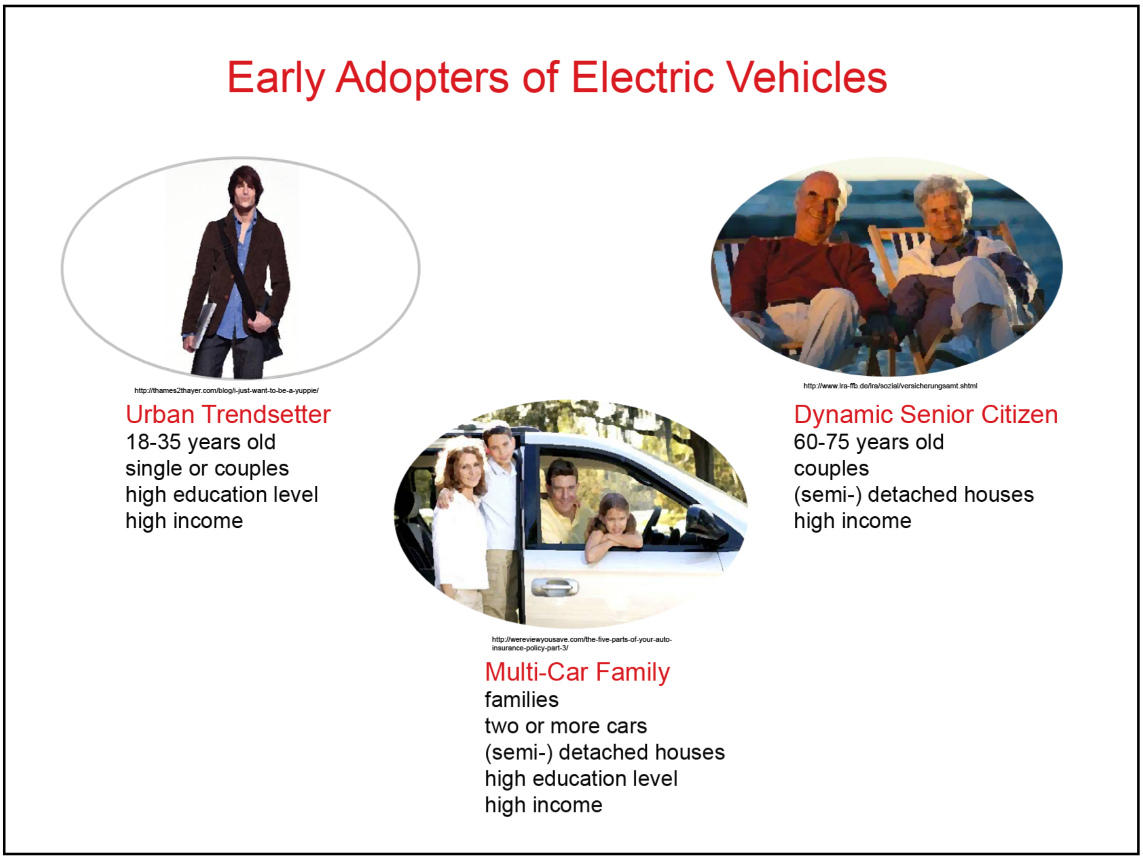

Figure 1: Hypotheses on Early Adopters of EVs

5. Model of the diffusion of EVs in the region of Stuttgart

In this section we will develop a model to simulate the diffusion of EVs in private households in the region of Stuttgart until the year 2020. The objective is, not to focus on the absolute figures of future EVs in the region, rather show spatial differences in diffusion between the single municipalities. The model is based on the Bass-diffusion model and takes into account the diffusion theory (section 2) as well as the assumptions on Early Adopters of EVs (section 4.3).

5.1 The Bass-diffusion model

The EV is a technological innovation in the automobile sector that has not gained any significant market share yet. As discussed in section 2.2, innovations usually spread according to specific rules. Based on the theory of diffusion of innovations, Bass (1969) developed a mathematical approach to model the diffusion of new products in marketing and innovation management science (Bass 1969; Mahajan, Muller et al. 1990). The Bass-diffusion model shows, how new products gain market share based on innovation and imitation effects. The main ideas of the model are derived from epidemiology, because the infection with a virus can be compared with the adoption of a new product. Similar to infection, the adoption of a new product results from contact or interpersonal communication with people that already own the product (imitation effect). Bass expanded the model by an innovation effect. He assumes that in the initial phase of diffusion, the so called innovators take their purchase decision independent of other adopters. These innovators adopt an innovation because of mass media messages about an innovation. According to Bass, the number of adopters of new products can be calculated as follows:

$$S(t) = \left(p + q * \frac{Y(t)}{m}\right)(m - Y(t)) \qquad (1)$$

$S(t)$	*sales*
p	*coefficient of innovation*
q	*coefficient of imitation*
$Y(t)$	*adopters*
m	*market potential*

The number of new adopters per time step results from adopters that purchased the product due to mass media message (coefficient of imitation p) and due to interpersonal communication channels (coefficient of imitation q). Every time step the number of adopters increases (Y(t)), while the number of potential adopters decreases (m-Y(t)). In a scenario, where there adoption results only from innovation (q=0), the diffusion curve shows a modified exponential form. In an imitation scenario (p=0), diffusion can be described as a logistic function. The combination of both effects leads to the development of a S-shaped curve of diffusion, which shows the cumulative number of adopters over time.

Empirical studies on diffusion processes demonstrate that the coefficient of innovation and imitation lie in defined intervals. The coefficient of innovation is relatively stable with an average value of 0.03. The coefficient of imitation has an average value of 0.38 with stronger deviations than the coefficient of innovation (Meade and Islam 2006).

Sterman (2000) used a System Dynamics approach to build the Bass-diffusion model in order to take feedback cycles into account (Sterman 2000). The main part in the model is the change from potential adopters (P) to adopters (A), which is driven by the adoption rate (AR) (Figure 2). The AR depends itself from two feedback cycles: the adoption from advertisement (corresponds to the coefficient of innovation p) and the adoption from word of mouth (corresponds to the coefficient of imitation q). The mathematical formulation is similar to the Bass-diffusion model, while the coefficient of imitation is the product of the contact rate c and the adoption fraction i. The contact rate is the frequency with which members of P and A encounter one another, while i is the proportion of contacts with A that are sufficient to induce a member of P to adopt.

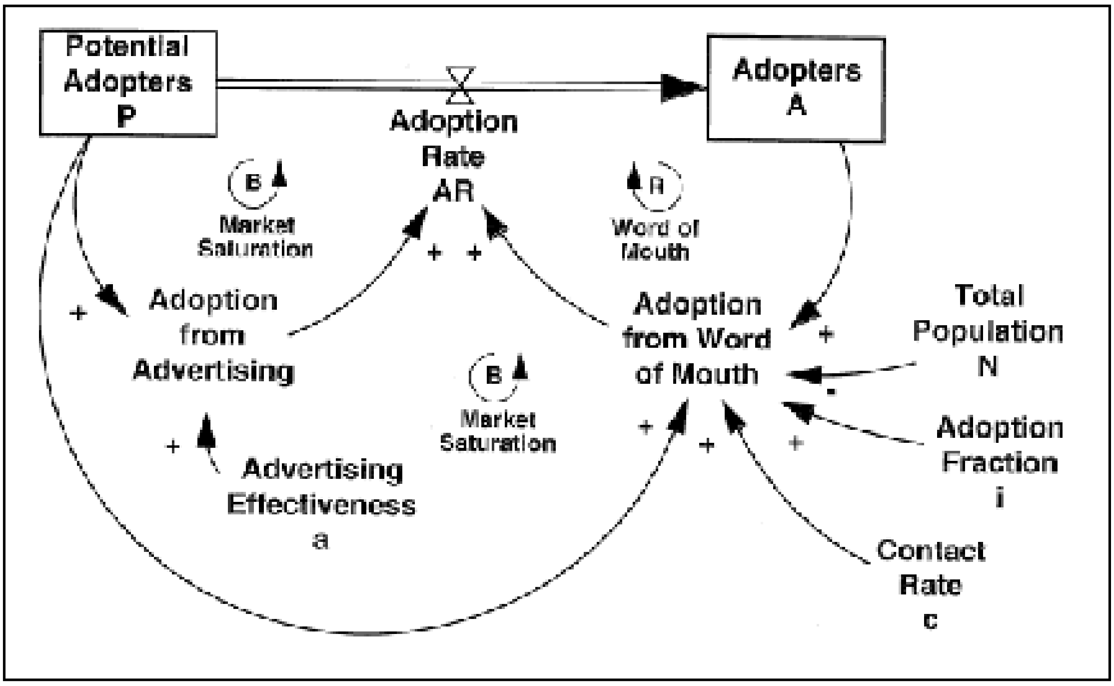

Figure 2: Bass diffusion model in System Dynamics according to Sterman (2000)

$$AR = a * P + c * i * P * \frac{A}{N} \qquad (2)$$

AR	*adoption rate*
P	*potential adopters*
A	*adopters*
N	*total population*
a	*advertisement effectiveness (=p)*
c	*contact rate*
i	*adoption fraction*
$c*i$	*coefficient of imitation (=q)*

In section 3.1 we mentioned that Cao (2004), Becker et al (2009) as well as Feller et al. (2009) used the Bass-diffusion model to model the diffusion of EVs. We will now apply the System Dynamics Diffusion approach of Sterman (2000) to model the diffusion of EVs in the region of Stuttgart and adjusting it by a spatial component which takes neighbourhood effects into account.

5.2 The Electric Vehicle Diffusion model

The EV-diffusion model was built with the software AnyLogic, which allows for multi-paradigm simulations (System Dynamics, agent based, event based). In this section we will shortly describe the data and spatial scale of the model, the modelling assumptions and the impact of parameter variation on modelling results.

5.2.1 Data and spatial scale

The data used for modelling is derived from the statistical office of the Land Baden-Württemberg, as well as from the city council and from the institute of applied social science (Infas), a geo-marketing research company (Infas 2010; Stadt Stuttgart 2010; StaLa 2010). Data from the statistical offices were available on municipality and urban district level. Data from Infas were available as point data and had to be aggregated on the municipality and district level. To examine spatial differences in the diffusion of EVs we chose the municipality level for simulation that is the smallest administrative unit for which data was available. Simulation on higher spatial resolution was only possible for the city of Stuttgart, where data was available on urban district level. Thus, the model was built for 178 municipalities of the region of Stuttgart and 23 urban districts of the city of Stuttgart.

5.2.2 Modelling assumptions

In the model we assume that until the year 2020 mainly Early Adopers will purchase an EV. Based on the hypothesis on Early Adopters (section 4.3), the number of potential adopters was calculated for each municipality or urban district of the region of Stuttgart. The number of potential adopters is the sum of “Urban trendsetter”, “Multi-car families” and “Dynamic senior citizens”. Furthermore we assume that there is a fraction of random adoption of the general population, which do not fall into the group of Early Adopters. The number of random adopters is added to the sum of Early Adopters. The share of random adoption is supposed to be equal for all municipalities/urban districts and can be separately chosen in the model.

In Table 1 the variables used to calculate the number of Early Adopters in each municipality/urban district are listed. Although income was part of the description of the hypotheses on Early Adopters it was neglected in the calculation, because it correlates with the education-level.

The number of potential “Urban trendsetters”, for example, equals the number of households in each municipality/urban district that is between 18-35 years old, that live as single or couple and that holds a university degree. The sum of Early Adopter households per municipality/urban district ranges between 2 and 6.5%.

Table 1: Variables used to calculate the number of Early Adopters in the municipalities/urban districts

Urban Trendsetter	Multi-Car Family	Dynamic Senior Citizen
Share of people 18-35 years old	Share of families	Share of people 60-75 years old
Share of singles and couples	Share of people with university degree	Share of couples
Share of people with university degree	Share of (semi-) detaches houses	Share of (semi-) detaches houses

In the model for each municipality/urban district four adopter groups exist (three Early Adopter types plus random adopters) while in each of these adopter groups a System Dynamics Bass-diffusion is implemented. The increase of EVs in each municipality/urban district thus depends on the total number of potential adopters as well as on the coefficient of innovation and imitation in the single adopter groups.

In the coefficient of imitation we included a neighbourhood effect, because we assume that for the diffusion it is important to take into account how many EVs one can see in the local environment. The purchase of an EV is more likely, the more EVs one can observe in the own municipality/urban district and in the neighbouring ones. Hence, every time step (year) the number of EVs increases depending on the number of EVs in the own and in the neighbouring municipalities/urban districts.

The adoption of EVs in a single adopter group (e.g. “Urban trendsetter”) can thus be calculated for every year by applying equation (2), while $\frac{A}{N}$ is calculated as follows:

$$\frac{A}{N} = \left(\frac{2}{3} * \frac{\sum adopters\ in\ one\ municipality}{\sum households\ in\ one\ municipality}\right) + \left(\frac{1}{3} * \frac{\sum_{i=1}^{neighbour.mun.} \frac{adopters\ in\ neighbouring\ municipalities}{households\ in\ neighbouring\ municipality}}{number\ of\ neighbouring\ municipalities}\right)$$

In this formula, the influences of the number of EVs in the own municipality/urban district and that from the neighbouring municipalities/urban districts is weighted in relation to each other.
We assume that the influence of the number of EVs in the own municipality/urban district is significantly higher, because people tend to spend more time in proximity to their homes. Thus, we chose to set the value for the own municipality to 2/3, while weighting the neighbouring municipalities with 1/3.
The timeframe of the simulation covers the period from 2010 to 2050, because we suppose that diffusion only reaches the saturation point in 2050, meaning that the number of new purchases of EVs will not increase afterwards. In our study we will focus, however, on the results from 2020. One time step in the simulation corresponds to one year.
We did not include demographic variations in the model. The demographic change will cause little shifts in the number of adopters in each adopter group. The total number of Early Adopters, will, however, remain almost constant. Furthermore, we assumed improvements in battery technology as well as rising oil prices in the future, which will improve the general conditions for adoption.

5.2.3 Model parameter

For every group of Early Adopters the parameters of the Bass-diffusion model can be chosen separately. In the following, the effect of each parameter on the model will be discussed.

- **Coefficient of innovation (a)**: The higher this parameter, the higher is the influence on advertisement and mass media on the purchase of EVs. In our model, the value can vary between 0.001 and 0.4. The higher the value, the more people buy an EV independently of the choice of the others and the diffusion process starts more rapidly in the beginning, which results in a rather linear curve.
- **Contact rate (c):** The higher the contact rate, the higher is the interpersonal communication between adopters and potential adopters. The contact rate determines

together with the adoption fraction i, the influence of "word of mouth" on the adoption rate. In our model the contact rate ranges between 0 and 1000 persons per year. The higher the value, the more the diffusion curve is S-shaped.

- **Adoption fraction (i):** This parameter determines the likelihood of adoption of a potential adopter when communicating with an adopter. If external parameters are changed, like oil prices or battery costs, the adoption fraction will increase globally in all adopter groups. Just as the contact rate, a high adoption fraction influences the development of a S-shaped curve. In our model the value will lie in the interval of 0.001 and 0.05.
- **Percentage of people adopting:** In the model one can choose for each group of Early Adopters, the percentage of people that will have purchased a car until 2050. We assume that almost all Early Adopters will have bought an EV until 2050, while the percentage of random-adopters of the general population will be lower. The percentage of people adopting also depends on global developments like rise of oil prices, change in political conditions (subsidies) or improvements in battery technology.
- **Neighbourhood radius:** This parameter indicates which municipalities/urban districts are neighbours, according to the position of their centroids. The bigger the radius, the more municipalities are taken into account to calculate the number of adopters in each time step. With a maximal radius of 30km every municipality would be adjacent to each other.

6. Scenarios of the diffusion of Electric Vehicles in the region of Stuttgart

In the following section scenarios of the diffusion of private owned EVs in the region of Stuttgart will be shown, demonstrating regional differences in diffusion and differences in adoption of the single adopter groups.

6.1 Baseline scenario

The objective of the baseline scenario is, to reach the goal of the national development plan on electromobility of the German government. According to this plan, we will have 1 million EVs driving on German roads until 2020, which accounts for 2.4% of the German passenger cars stock. Taking the same passenger car/EV-ratio, we would have about 34.000 EVs in the region of Stuttgart until 2020. In this simulation run, the number of 34.000 EVs will be given for 2020, while we want to figure out differences in the spatial diffusion of EVs depending on the location and number of the different adopter types.

In this scenario we assume that 90% of Early Adopters will have purchased an EV until 2050 ("Urban trendsetter" (UT), "Multi-car families" (MF), "Dynamic senior citizen" (DS)), while only 30% of the remaining general population will have adopted the technology. We expect the UT to be more innovative than the other adopter types which implies that they are more sensitive to advertisement. Thus, the advertisement effectiveness is set to 0.02 for the UT, to 0.01 for the MF and is even lower for the oldest group of DS with only 0.005. Since we assume that the general population is usually not interested in technological innovations, the parameter is set to 0.001. Concerning the contact rate, we suppose the UT to be the most active group of Early Adopters, which communicate with 700 persons per year, while the MF and the general population have an average number of 500 contacts. The DS only communicates with 300 persons per time step. Furthermore we presume that the UT has to meet less adopters to get convinced of the EV. If they meet an adopter they purchase an EV with the likelihood of 2%, corresponding to an adoption fraction of 0.02. For FM and DS the adoption fraction is set to 0.01. Of the general population only a small proportion will adopt an EV randomly, thus the adoption fraction is very low (0.0008%). In the baseline scenario we do not take into account neighbourhood effects. This means, that the adoption of EVs in one municipality/urban district only depends on the existing number of EVs in the own municipality/urban district.

Figure 3**Error! Reference source not found.** shows the simulation results indicating differences in spatial distribution of EVs. In the year 2020 almost 40% of Early Adopters have purchased an EV in the region of Stuttgart, corresponding to a number of about 17,800 EVs. Although innovation and imitation coefficients of the general population are set to much lower values, the general population has purchased already about 16,200 EVs. This is due to the high number of remaining households in the region that are included in the calculation. The highest total number of EVs at the Early Adopters can be found in the group of the DS (8,220), followed by MF (4,940) and UT (4,660).

In **Error! Reference source not found.** one can also discover spatial differences in diffusion. Thus, the highest number of EVs can be found in the districts of the city of Stuttgart, followed by the bigger towns of the region, like Esslingen, Ludwigsburg, Leonberg, Böblingen and Sindelfingen. Spatial differences exist also between the single adopter types (see pie charts). Some municipalities/urban districts are dominated by Early Adopters (red, green, blue) others show higher adoption rates of the general population (purple). A comparison of the number of EVs present at each adopter type shows that UTs (red) dominate the central urban districts in Stuttgart, while the number of EVs at MFs is higher in the rural municipalities of the region. The DS have similar shares of EVs in urban and rural areas.

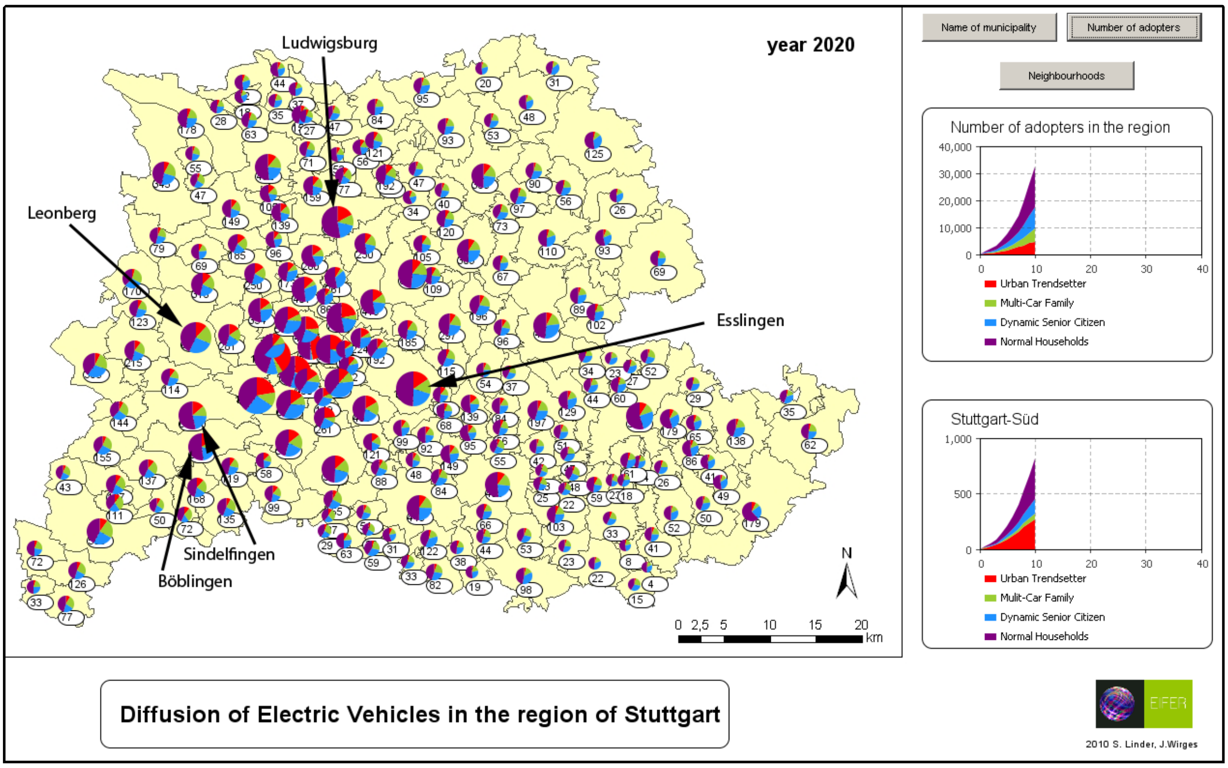

Figure 3: Baseline scenario in the region of Stuttgart

6.2 Baseline scenario with neighbourhood effects

This scenario is calculated with the same parameter values as for the baseline scenario. The only difference is that diffusion also depends on the number of EVs in the neighbouring municipalities/urban districts. Here, the neighbourhood radius is set to 10 km, because this is the average distance travelled per day (Vollmer, Kunert et al. 2004). This implies that for each municipality/urban district the number of EVs of municipalities/urban districts that lie within a distance of 10 km are included in the analysis.

Figure 4 depicts the result of the simulation run for the year 2020. The total number of EVs increases only slightly to 35.100. The small effect of EVs from neighbouring municipalities/urban districts might be due to the fact that neighbouring units are only weighted by one third (see equation 3). Another reason might be that the value for neighbouring units represents an average of EVs which does not deviate significantly from the number of EVs in the own municipality/urban district.

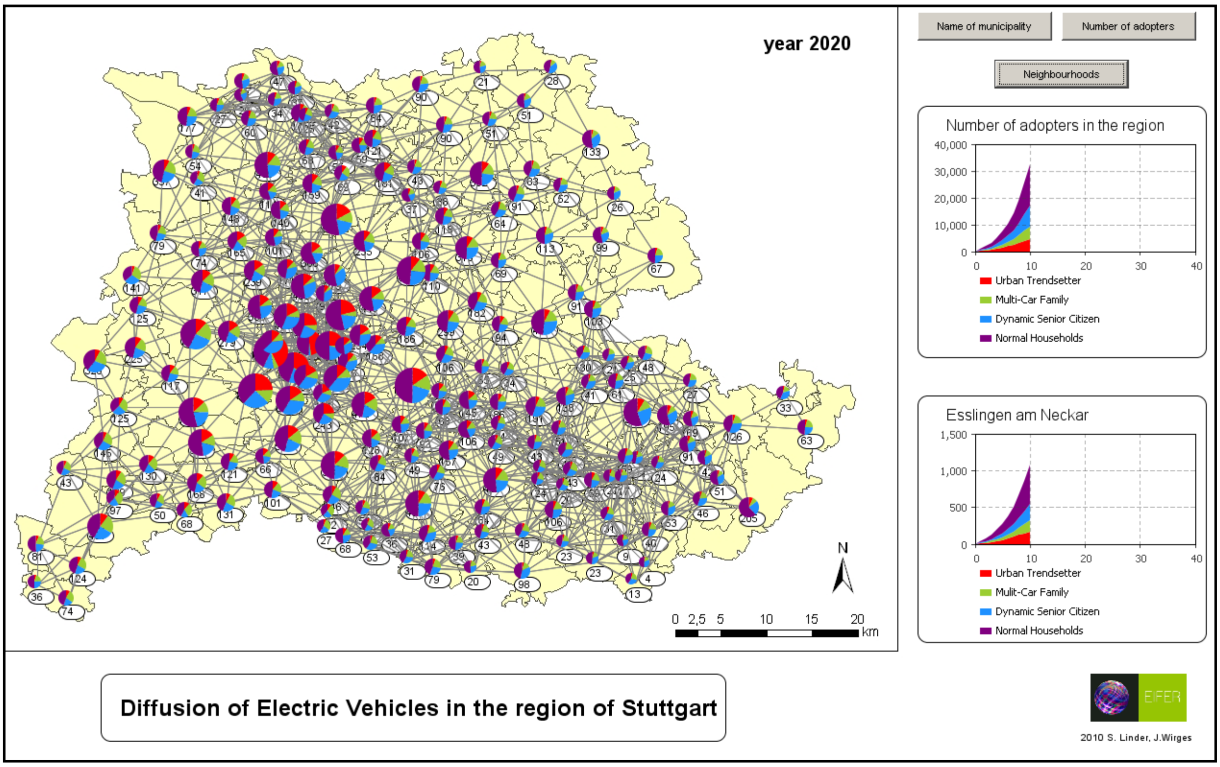

Figure 4: Baseline scenario with neighbourhood effects

6.3 Scenario – "Early Adopters do not exist"

In this scenario we assume that all households have the same attributes, meaning that no Early Adopters exist. Thus, all parameter values are set to those of the general population. Therefore only 30% of Early Adopters will purchase an EV until 2050 and their values of the innovation and imitation coefficients are significantly lower than in the baseline scenario.

In 2020 only about 7420 households will have adopted an EV (Figure 5). Due to the low innovation and imitation coefficients of the general population, the diffusion does not take off. We can conclude that the higher adoption rates of the Early Adopters triggered the diffusion in the beginning in the baseline scenario which also allowed the normal population to adopt EVs in much higher rates than if there were no Early Adopters present.

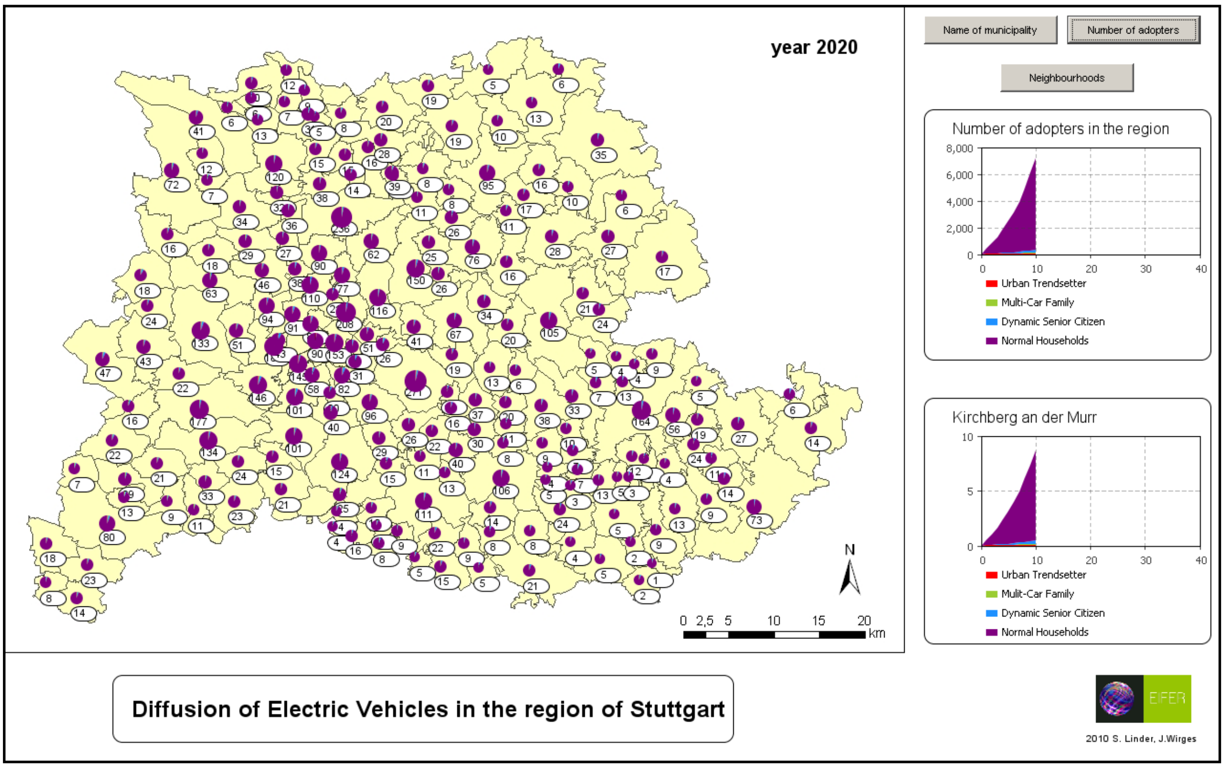

Figure 5: Scenario without Early Adopters

7. Discussion and Conclusion

The aim of this study was to develop scenarios for the diffusion of EVs in private households in the region of Stuttgart up to 2020 and to analyse whether spatial differences in the distribution exist. Since until today almost no EVs are used as private passenger cars, no real data exist to calibrate the model. Therefore hypotheses on Early Adopters of EVs were built, based on the theory of diffusion of innovations, case studies on early adoption of EVs and surveys of people interested in the purchase of an EV. The resulting numbers of EVs should not be seen as quantitative forecasts of EV diffusion, but rather be used to get an idea on the relative

significance of the different adopter types as well as the differences in future spatial distribution of EVs.
One can also question the choice of the parameter settings of each adopter type. The values of the innovation and imitation coefficient are adjusted according to the hypothesis on the attributes of each Early Adopter type. In our opinion the absolute value of the single parameter is not as important as the relation between the different adopter types. In the first years of EV market penetration empirical data will be available so that the model can be calibrated.
In this model we investigated the diffusion of EV in private households. The current development shows, however, that many enterprises start to use EVs in their fleets, thus representing another group of Early Adopters. The EV fleets will be visible on the streets and constitute a well example for early use of EV, possibly influencing private households on their purchase decision. An extension of the model is already in progress to integrate the impact of enterprise fleets on diffusion of EVs.
Finally we can conclude that spatial differences in the diffusion of EVs up to 2020 become apparent: the highest number of EV-holders will be found in the urban areas of the region. There exist also differences in the number of EVs present at each early adopter-type: The “Urban trend-setter” is prevalent in the central districts of Stuttgart, while the “Multi-car family” is mostly located in the more rural municipalities of the region of Stuttgart. The “Dynamic senior citizen” is almost equally distributed in the urban and rural areas. Neighbourhood effects only play a minor role in diffusion, the way they are implemented in the model. This has to be validated with empirical data. A comparison of the different scenarios shows that Early Adopters are important to trigger the process of diffusion in the beginning, because of their higher coefficients of innovation and imitation. Thus, a critical mass of Early Adopters is necessary to initiate the diffusion also resulting in higher adoption rates of the general population.
The results of the spatial distribution of potential adopters of EVs can be used for automobile industry’s marketing campaigns as well as to identify the regional demand for EV charging infrastructure.

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